Retrofitting and Rehabilitation of Civil Infrastructure
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Lecture 35
Design Approach for Shear Strengthening

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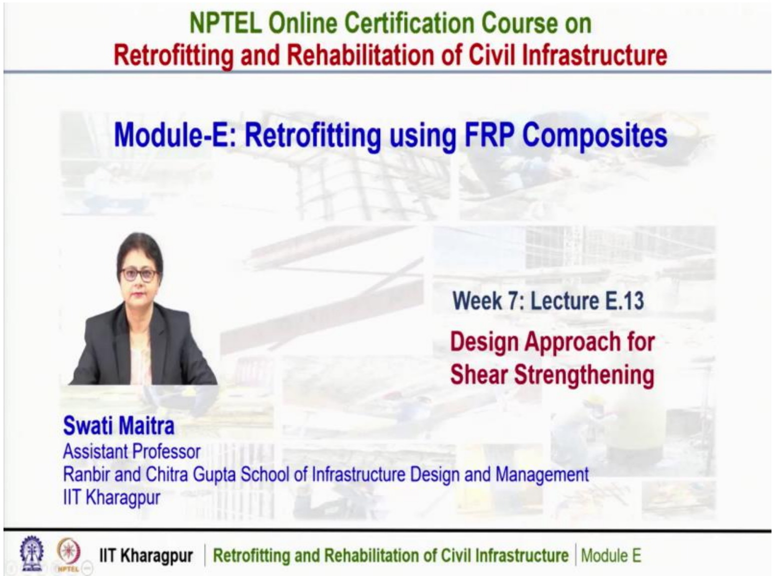

Hello friends, welcome to the NPTEL online certification course Retrofitting and Rehabilitation of Civil Infrastructure. Today, we will discuss module E, the topic for module E is retrofitting using fiber reinforced polymer composites.

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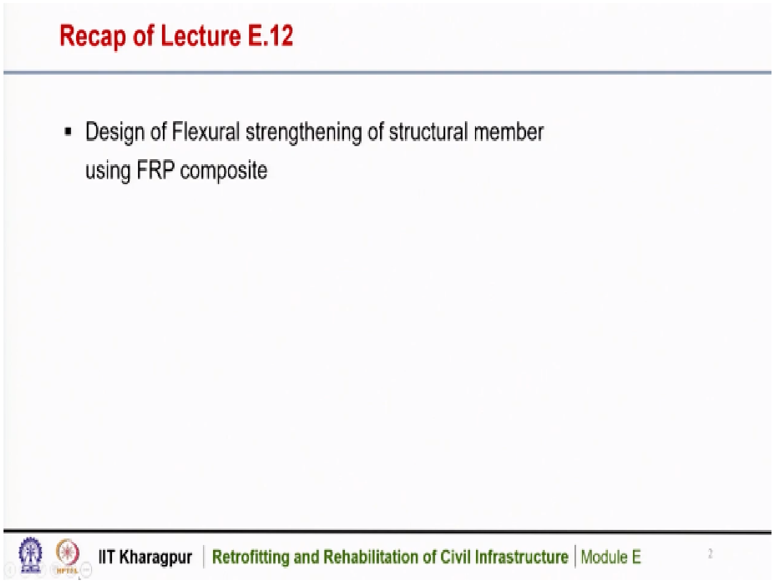

In the previous lecture we have discussed the design of flexural strengthening of structural member using FRP composites. We have discussed a design example for flexural strengthening of a beam using CFRP composite.

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Today, we will discuss the design approach for shear strengthening of structural members using fiber reinforced polymer composites. We have seen in our previous lectures that the structural members can be strengthened to improve their flexural capacity, to improve their shear capacity and actual capacity.

So, shear strengthening of structural members like beams are also very important and it is important to strengthen the structures so that the shear capacity is improved. So, today we will discuss the design approach for shear strengthening of structural members using FRP composites.

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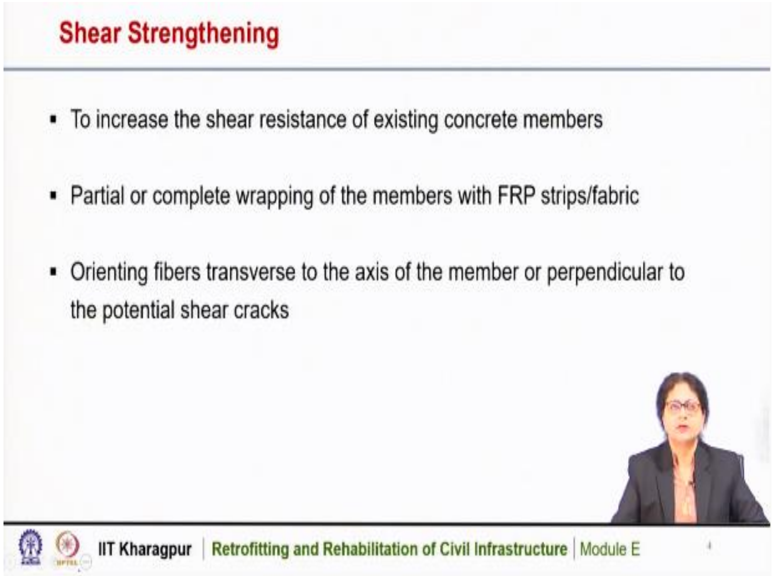

Shear strengthening is aimed to increase the shear resistance of existing concrete members and we have seen that several research works have been done to understand the behavior of the FRP retrofitted members in improving their shear capacity. The shear capacity can be improved by partial or complete wrapping of the members with FRP strips or fabrics and there are different patterns have been used, different schemes of FRP placement have been used by researchers and with that the shear capacity of the members are increased.

The fibers are oriented transfers to the axis of the member or perpendicular to the potential shear cracks and that helps in improving the shear capacity of the members.

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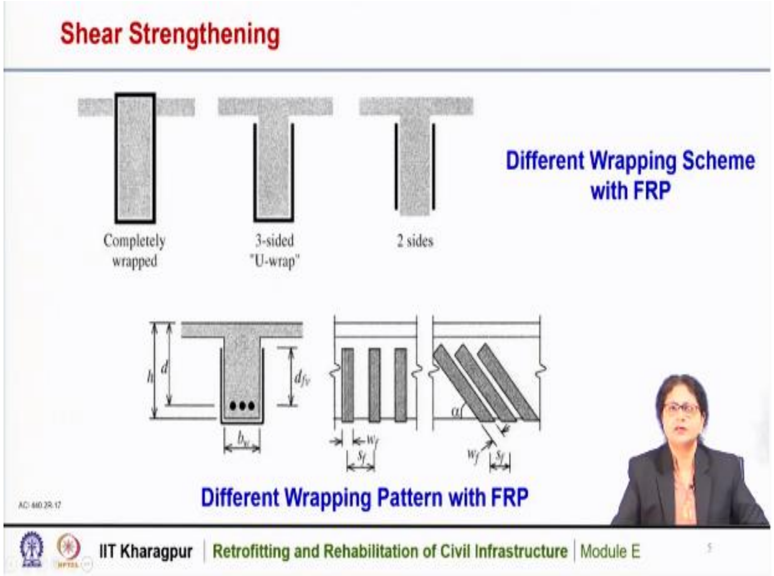

There are different wrapping scheme and wrapping pattern different researchers have tried and that could be continuous or it could be intermittent or there could be at any angle. So, there are different wrapping pattern that are possible or different wrapping scheme around the member.

In the design of a shear strengthening however these have been considered by the American Concrete Institute guideline. So, for shear strengthening the beam can be either completely wrapped, as we can see here, either completely wrapped or it is wrapped at its 3 sides or we call it U-wrap, so 3-sided U-wrapping or it could be on 2 sides.

So, the FRP composite can be placed ah on 2 sides of the beam member and in these 3 cases the shear capacity of the member increased significantly. The most effective is the complete wrapping scheme, next is 3-sided U-wrapping and next is 2-sided wrapping. So, these are the 3 wrapping schemes that have been considered and the wrapping pattern may be also 2 or 3 types.

So, it could be FRP is placed perpendicular to the length of the member and it is intermittently placed. So, this is the width of the FRP strip and they are placed at a spacing of s_f, center to center distance between the strips can be there. So, this is the intermittent placement of the FRP strips and they are placed vertically or perpendicular to the length of the member, it could be also at some angle as we can see here at an angle of alpha to the length of the member. So, it could be at an angle also.

In many of the cases the shear cracks that are developed are making an angle of 45 degree, so we can provide the FRP strips perpendicular to the possible shear cracks. So, FRP can also be placed perpendicular to the possible shear cracks or at some angle of alpha and it can be placed intermittently or it could be placed continuously, that means the spacing is the same as the width of the member. So, then it is termed as continuous wrapping pattern.

Ut could be placed at the shear zone near the support or entire length. So, these are the different wrapping patterns and wrapping schemes that has been considered in the American Concrete Guidelines and with these schemes and wrapping pattern the shear capacity of the beam members is increased significantly.

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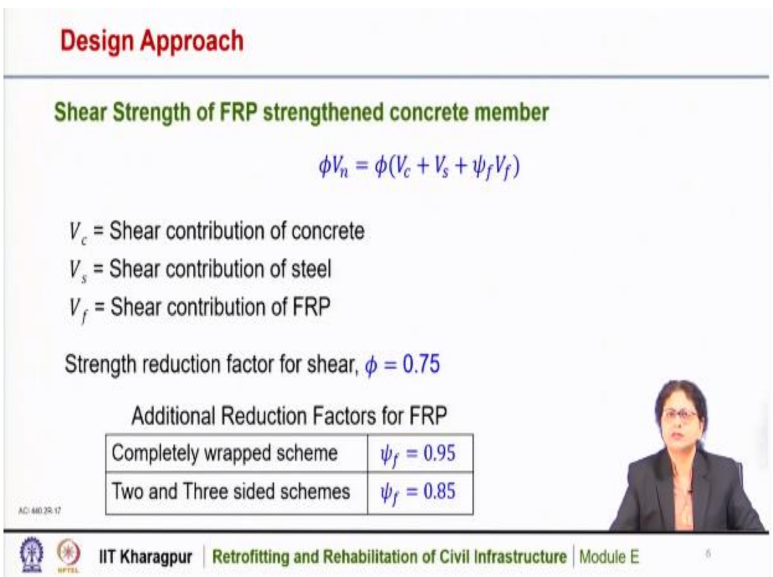

So, we will discuss the design approach for shear strengthening of the FRP retrofitted concrete members. The total shear capacity of the FRP strengthened member is termed as ϕV_n that is the total shear capacity of the FRP strengthen member and that shear strength is due to the contribution of the concrete, steel and the FRP.

$$\phi V_n = \phi(V_c + V_s + \psi_f V_f)$$

So, V_c is the shear contribution of the concrete, V_s is the shear contribution of the steel stirrups and V_f is the shear contribution of the FRP reinforcement, which is applied on the beam either 3 sided or 2 sided or completely wrapping.

So, this is the total shear capacity of the FRP strengthened concrete member, it is the summation of the shear contribution of concrete, steel stirrups and the FRP reinforcement. Now, ϕ is a strength reduction factor as we have seen in case of flexure also there is a strength reduction factor and for shear also the value is different. So, this value for ϕ is 0.75, for shear and that has to be considered and the factor ψ_f that is another strength reduction factor for FRP. And this strength reduction factor has been considered to take care of the uncertainties in the properties of the FRP.

So, this ψ_f here has been taken considering the uncertainties of the FRP and as well as the different wrapping scheme. So, for the completely wrapped system this ψ_f is equal to 0.95 whereas for 2 sided or 3 sided scheme it is 0.85. So, these are the additional strength reduction factor for FRP that is to be considered depending on the wrapping scheme.

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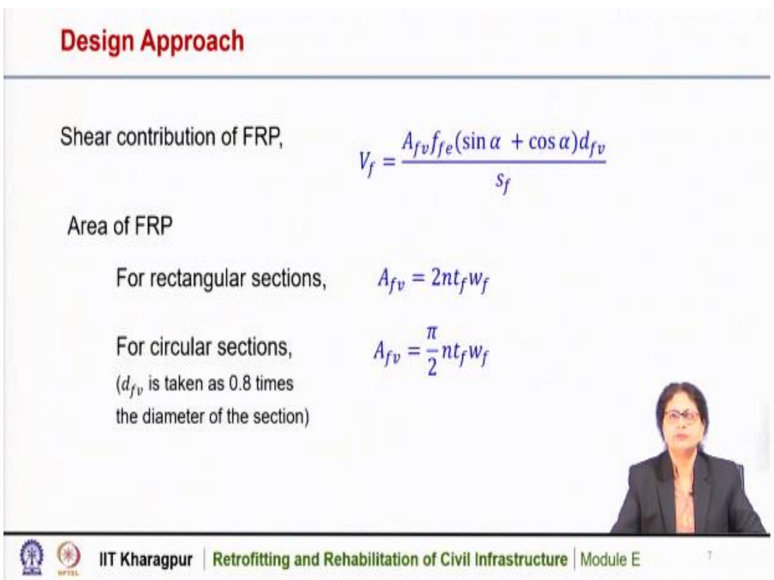

Now, we need to estimate the shear contribution of the FRP that is the most important thing what is the contribution of the FRP when it is wrapped either intermittently or complete wrapping or a 3 sided, 2 sided or at making some angle. So, what is the contribution of the FRP in the member? So, that is given by this relationship V_f that is the shear contribution of the FRP, $V_f = A_{fv} f_{fe}(\sin\alpha + \cos\alpha)\ d_{fv}/s_f$, A_{fv} is the area of the FRP, f_{fe} is the stress in the FRP, α is the angle of the FRP strips, d_{fv} is the depth of the fiber and S_f is the spacing.

So, this relationship gives us the shear contribution of the FRP and this depends on how much area of FRP we are providing, what is the stress coming on it and what is the wrapping pattern, whether it is at some angle or not that influences the shear contribution by the FRP.

The area of FRP for rectangular sections can be obtained as $A_{fv} = 2nt_f w_f$, n is the number of plies, t_f is the thickness of the FRP, w_f is the width. So, this gives us the area of the FRP and it is on 2 sides. So, this gives the area of the FRP for rectangular sections, we can also have circular sections and for that we can use this relationship $A_{fv} = (\pi/2)\ nt_f w_f$.

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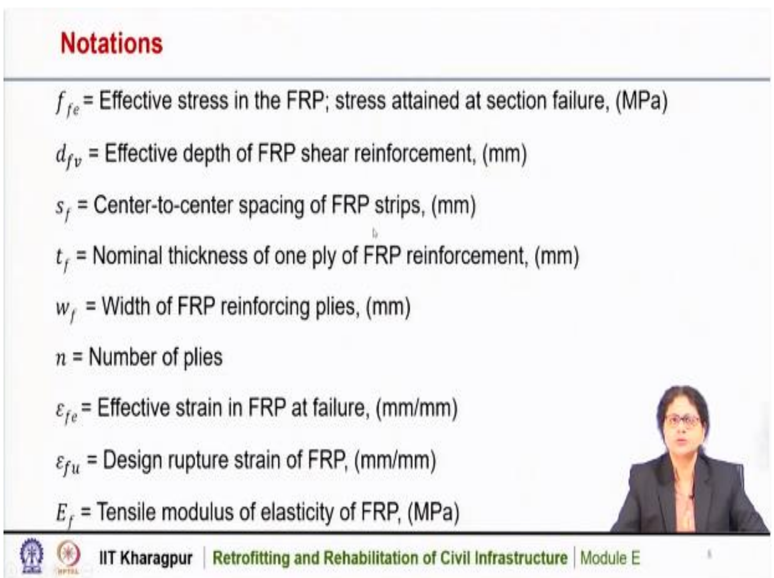

So, these are the typical notations that are used for today's lecture, f_{fe} is the effective stress in the FRP and this stress attained at section failure, d_{fv} is the effective depth of FRP shear reinforcement, S_f is the center to center spacing of the FRP strips that are shown in the sketch in the previous slide, t_f is the thickness of the single ply of FRP, w_f is the width of the FPR reinforcing ply, n is the number of plies, ε_{fe} is the effective strain in

FRP at failure, ε_{fu} is the design rupture strain of FRP and E_f is the tensile modulus of the elasticity of FRP. So, these are the standard notations that are used.

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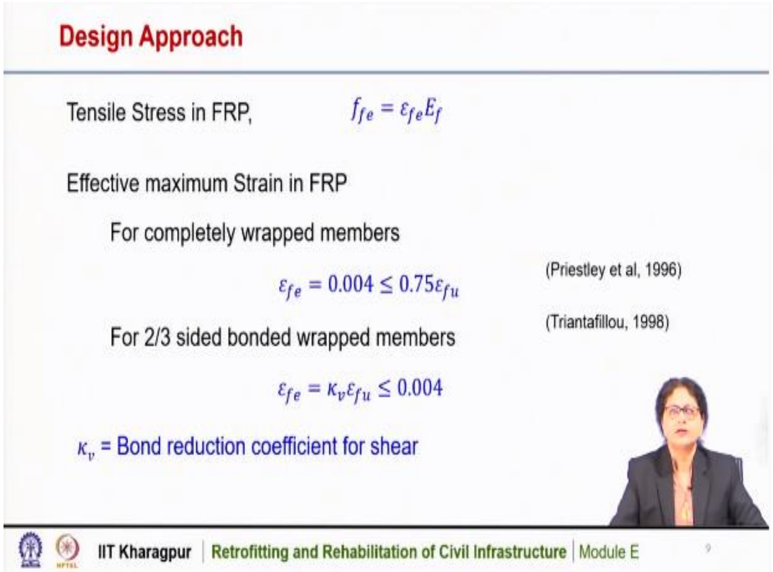

So, we need to find out the tensile stress in the FRP, we have discussed that what is the area of FRP and here how we can estimate the tensile stress in the FPR. So, $f_{fe} = \varepsilon_{fe}E_f$ and we have to find out the maximum strain in the FRP. So, for completely wrapped system the strain in the FRP that is ε_{fe} is restricted as point 0.004 and that should be less than equal to $0.75\varepsilon_{fu}$, that is the ultimate strain of FRP.

For completely wrapped system it has been seen from several experiments that we have also discussed in the previous lectures that for completely wrapped system the failure is due to rupture of the FRP. So, the predominant mode for the FRP strengthen member where it is completely wrapped that is due to the rupture of the FRP.

So, the effective strain in case of completely wrapped system is been kept as 0.004 and that should be less than 0.75 times the ultimate strain in the FRP. So, this is the effective strain for completely wrapped system and this is by the research works of Priestly et al in 1996 and for 2 and 3 sided bonded members it has been seen that generally the failure is due to debonding.

So, for the 2 sided wrapped or 3 sided wrapped beam members the failure is mostly due to debonding. So, here in this case the strain in the FRP has been considered by using the debonding thing or using the bond reduction coefficient. So, the strain in the FRP has been estimated as $\varepsilon_{fe} = \kappa_v \varepsilon_{fu} \leq 0.004$.

So, generally the 2 sided or 3 sided wrap members fail due to debonding, that is debonding of the FRP from the concrete substrate. So, a bond reduction coefficient has been used in case of 2 sided or 3 sided wrapped members. So, these coefficients have been determined from the several research works by Triantafillou and from that the expressions have been developed.

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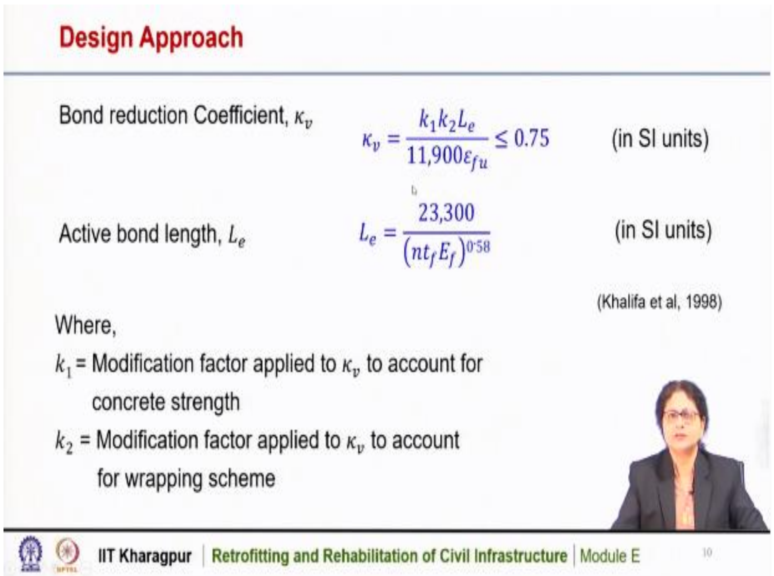

So, the bond reduction coefficient κ_v is expressed by this relationship $\kappa_v = (k_1 k_2 L_e)/(11{,}900\varepsilon_{fu}) \leq 0.75$. L_e is the effective bond length, so for 2 sided or 3 sided member there is an effective bond length and this is termed as L_e or active bond length and that is expressed by this expression.

So, this relationship gives the effective bond length $L_e = 23{,}300/(nt_f E_f)^{0.58}$ and k_1 and k_2 are the 2 modification factors, k_1 is the modification factors for the concrete strength and k_2 is the modification factor applied to κ_v to account for the wrapping scheme. So, these 2 are the modification factors that need to be considered while estimating the bond reduction coefficient κ_v.

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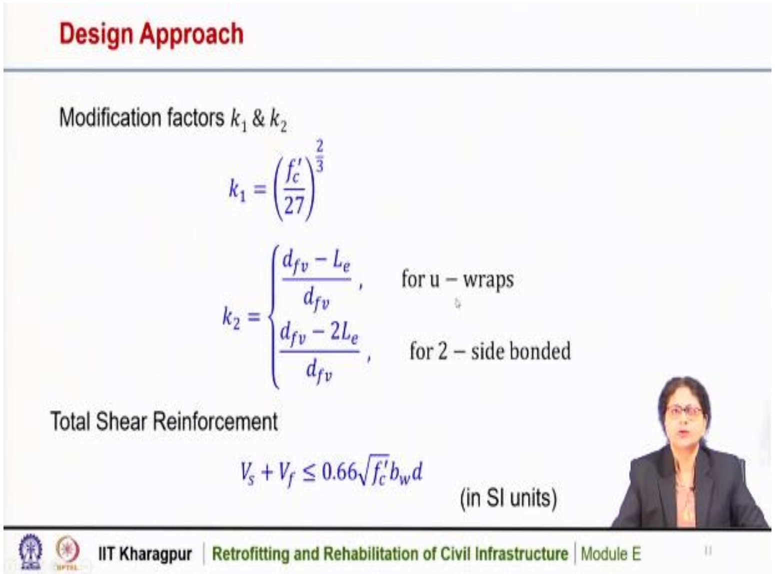

So, k_1 can be expressed as $k_1 = (f_c'/27)^{2/3}$ and k_2 is the modification factor depending on the wrapping scheme of the FRP. So, there are 2 expressions for the 2 different wrapping schemes, one is for U-wrapping and another is for 2-sided wrapping. So, k_2 the first expression is to be used for U-wraps and the second expression is to be used for 2-sided wrapping. So, the k_1 and k_2 are the modification factors for estimating the κ_v that is the bond reduction coefficient.

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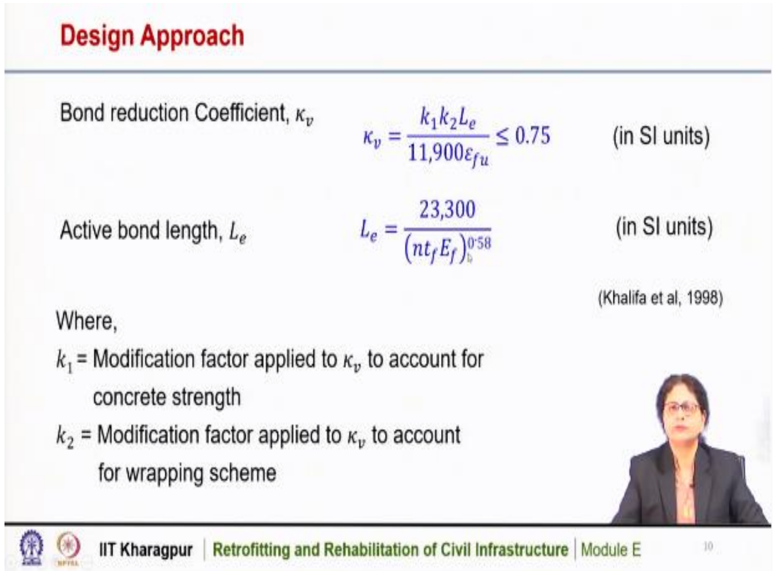

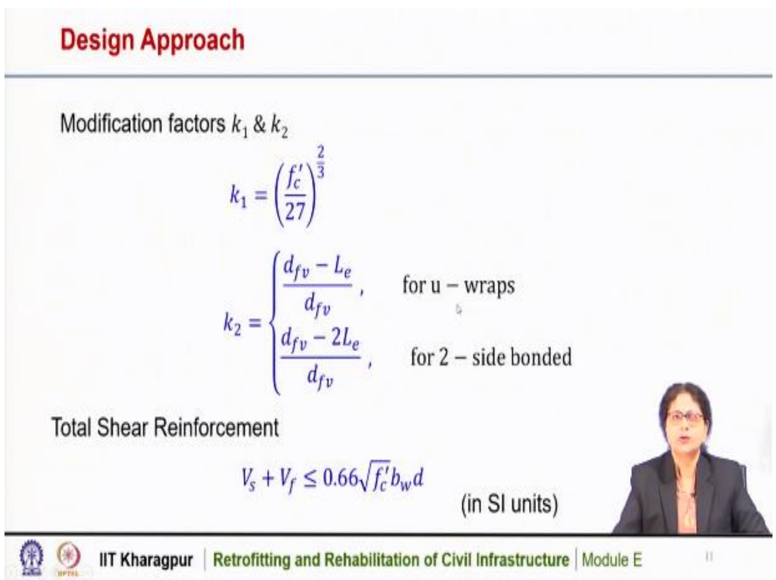

And this is the expression for L_e that is the active bond length, so by estimating the k_1, k_2 and L_e we can find out the κ_v that is the bond reduction coefficient and once we calculate the bond reduction coefficient, we can find out the contribution of the FRP in shear strengthening.

So, the total shear reinforcement can be estimated as $V_s + V_f \leq 0.66\sqrt{(f_c')}\, b_w d$, V_s is the contribution of the steel stirrups and V_f is the contribution from the FRP.

So, by knowing the contribution of the steel stirrups by estimating the contribution of the FRP and also the contribution of the concrete we can find out the total shear capacity of the FRP strengthened member. So, that should be more than the required shear strength and if it is more than the required shear strength then the system is safe.

So, this is the design approach here for the 3 sided wrap or for the 2 sided wrap mainly the failure mode is due to debonding and that is why it has been considered a debonding, bond reduction coefficient has been developed, which considers the modification factors for concrete strength and the wrapping scheme as well as the active bond length.

And for all 4 sides wrapping it has been seen that the failure is due to mostly by FRP rupture. So, a limiting value for the strain has been considered for the 4 sided wrapped members. So, we have to calculate the total shear contribution of the steel stirrups, the total shear contribution of the FRP system and the total shear contribution from the concrete and that should be more than the strength, shear strength requirement, if it is so then the design can be considered as safe.

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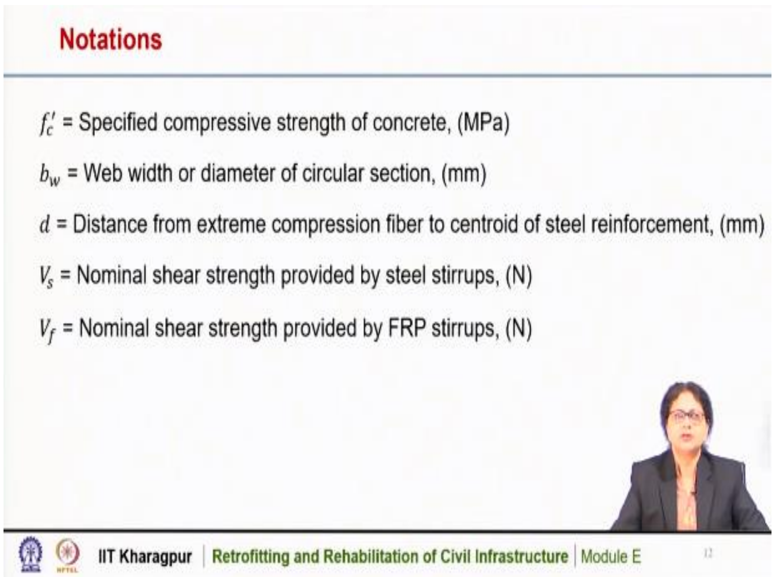

So, these are the notations as we have discussed $f_c{}'$ to the specified compressive strength of concrete, b_w is the width or diameter of the circular section, d is the distance from extreme compression fiber to centroid of steel reinforcement, V_s is the nominal shear strain provided by steel stirrups and V_f is the nominal shear strain provided by the FRP stirrups.

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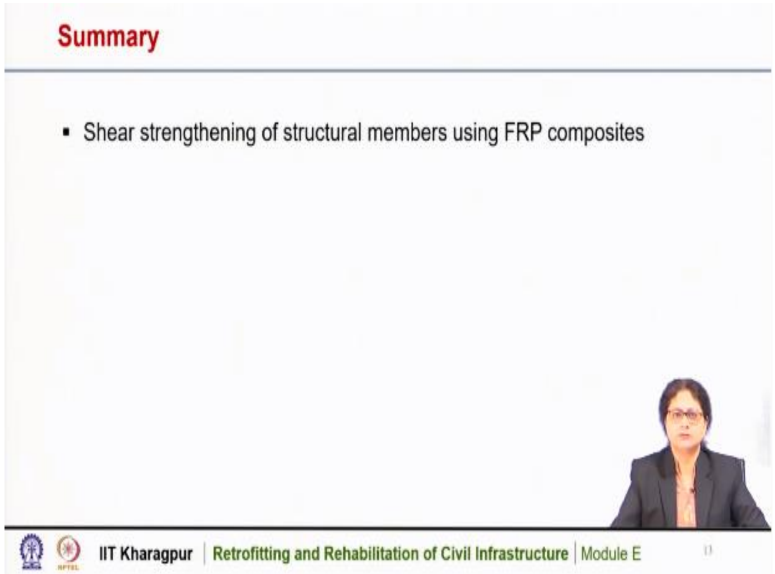

So, to summarize we have discussed today the design approach for shear strengthening of structural members using FRP composites, the 2 different types of failure modes have been considered depending on the wrapping scheme there may be different types of wrapping scheme that is it could be all 4 sided wrapping or it could be 2 sided or it could be 3 sided or the FRP could be placed continuously at the support or at the full length or it could be placed intermittently.

And depending on the wrapping scheme the shear contribution of the FRP varies and the total shear contribution by the concrete, by the steel stirrups and by the FRP governs the total shear capacity of the FRP retrofitted member. Thank you.